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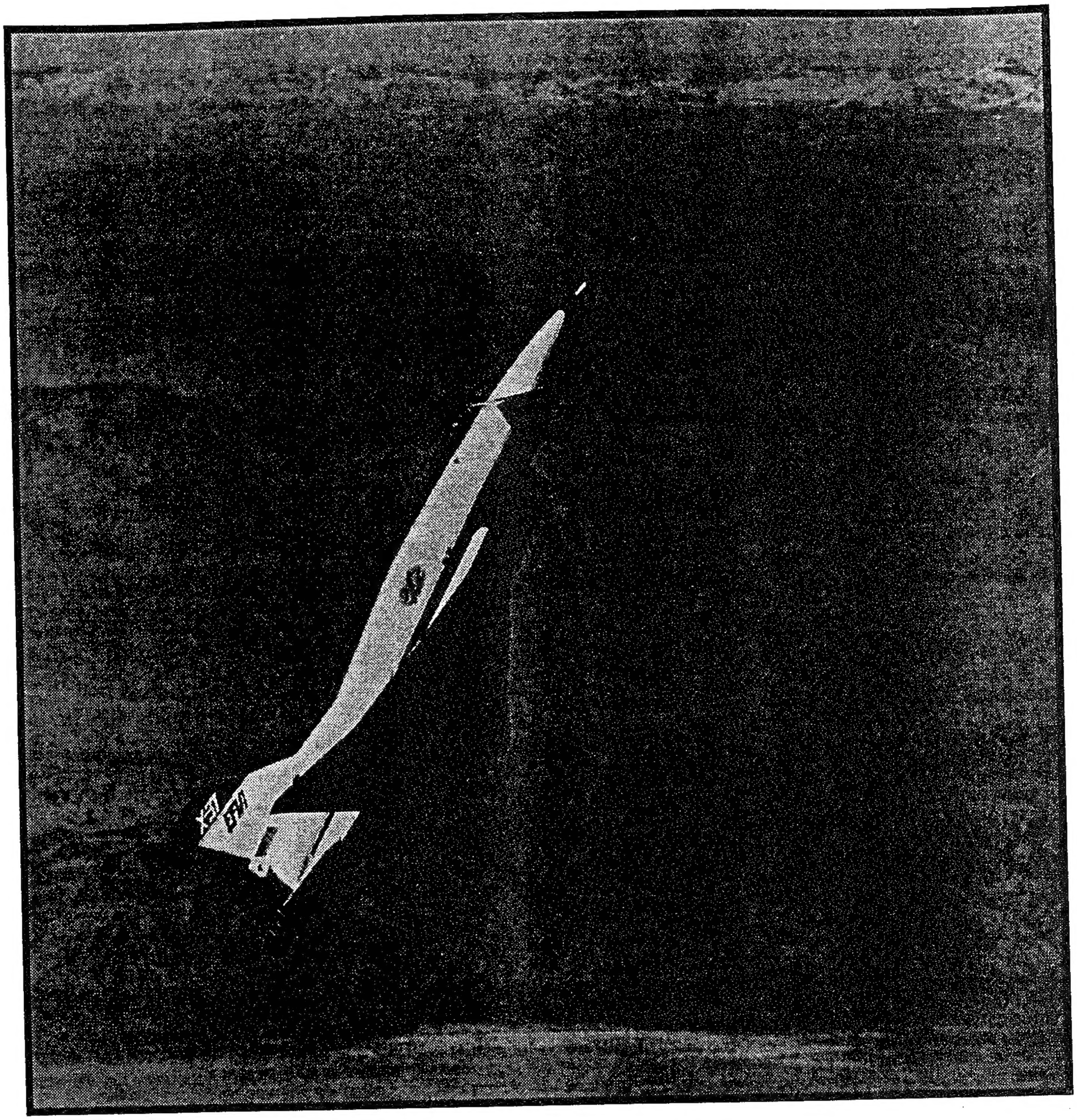
TAKING AN X-AIRPLANE TO THE PARIS AIR SHOW



Presented at

The Society of Experimental Test Pilots Symposium
29 September 1995
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TAKING AN X-AIRPLANE TO THE PARIS AIR SHOW

INTRODUCTION

X-31 EFM PROGRAM

The X-31 Enhanced Fighter Maneuverability (EFM) Program had four goals when the program was initiated in the late 1980's:

(1) Rapid demonstration of high agility maneuvering concepts.

(2) Investigation of tactical benefits of EFM technologies.

(3) Development of design requirements and to provide a database for future airplane applications.

(4) Validation of an international low cost prototyping program.

Two X-31 demonstrator airplanes began flight test at Rockwell's Palmdale Test Center in 1990. The airplanes employed multi-axis thrust vectoring as the enabling technology for Enhanced Fighter Maneuverability. After completing initial post-stall envelope clearance flights at Palmdale, the two airplanes and the X-31 program were moved to the NASA Dryden Flight Research Center in early 1992 to complete envelope expansion and to conduct close-in-air combat testing.

The X-31 program was managed by the International Test Organization (ITO). The lead government agencies were the Advanced Research Projects Agency and Germany's Federal Office of Defense Technology and Procurement. The on-site government team members were the U.S. Navy, German Ministry of Defense, NASA, and the U.S. Air Force. Rockwell International and Daimler-Benz Aerospace were the contractor

members of the ITO. The X-31 was the first international flight research program of an "X-Airplane".

X-31 ACCOMPLISHMENTS

The X-31 Program met all its program goals and flew 580 flights, the most of any "X-Airplane". Envelope clearance flights demonstrated that multi-axis thrust vectoring provided "carefree" post-stall (PST) maneuvering to 70 deg Angle of Attack (AOA). The dramatic benefits of EFM in close-in-combat were validated in over 400 engagements against F/A-18, F-16, F-14D, and F-15 airplanes. With all program objectives met, the X-31 team conducted a series of research flights to demonstrate the potential of a tailless strike/fighter airplane design. The quasi-tailless test was sponsored by the Joint Advanced Strike Technology Program and clearly demonstrated the capability for thrust vector control of a directionally unstable tactical airplane.

PARIS AIR SHOW OPPORTUNITY

With the successful completion of all program goals and the dramatic maneuver capability demonstrated by the X-31, planning was begun in late 1994 to take the X-31 to the 1995 Paris Air Show. The X-31 would showcase U.S. and German technology and specifically demonstrate the post-stall maneuver capability provided by multi-axis thrust vectoring. The air show demonstration would clearly show that thrust vectoring had matured and was ready for operational development.

From the beginning, it was recognized that safety would be the key issue to the success of the X-31 in preparing for and flying in the air show. This paper will discuss some of the safety issues involved in taking an "X-Airplane" to the Paris Air Show and actions the X-31 team took to reduce the risks.

AIRPLANE DESCRIPTION

The X-31 is a rather small (12,500 lb empty weight), single seat, single engine research airplane (figure 1) with

three thrust vector vanes hinged on the airframe behind the engine nozzle. It carries 4,100 lb of fuel and is powered by a General Electric F404-GE-400 jet engine. Maximum use of existing systems helped to keep costs low with the canopy, ejection seat, control stick, throttle, HUD, and DDI from the F/A-18. A drag chute replaced the spin chute at the base of the vertical tail for European flight operations. Since there is one radio, one attitude source, and no integrated navigation system, flight operations were day VFR only. A hand-held Global Positioning System (GPS) receiver was carried in the airplane during European ferry flights and during the air show.

The X-31 flight control system is digital with no analog or mechanical back-up (figure 2). Multi-axis thrust vectoring is fully integrated in the flight control system. The flight control laws provide both a conventional flight mode and post-stall mode. The conventional mode limits AOA to 30 deg and can be flown with thrust vectoring on or off (pilot selectable). For post-stall flight, TV must be operating and the PST mode engaged by the pilot. Both modes are AOA command systems below 320 KCAS. At speeds above 320 KCAS, the control laws provide "apparent G" command. Roll commands (lateral stick) provide stability axis rolls about the velocity vector with zero sideslip.

PARIS AIR SHOW SAFETY CHALLENGES

PAST AIR SHOW LESSONS LEARNED

The Society of Experimental Test Pilots "Air Show Committee Report" was the starting point for our preparation for the Paris Air Show. The report and background materials provided by the Society allowed the X-31 team to learn from the successes and failures of other Society members. The report was distributed throughout the team and provided a sobering and realistic insight into the challenges that are involved in surviving an air show. Anyone involved in an air show must get the "Air Show Committee Report" file and heed its advice.

RECOVERING FROM THE MISHAP

In January 1995, just as Paris Air Show planning was accelerating, X-31 aircraft (A/C) #1 was lost in a mishap. After the completion of the test cards and during return to base, the single total pressure source on the noseboom was blocked by ice while in clear air in conditions of unusually high humidity. Though dual air data computers provided electrical redundancy, the blocked total pressure port allowed erroneous airspeed values to be fed to the flight control computers, which resulted in improper gains for the actual flight condition and caused the airplane to depart. The pilot ejected and the airplane crashed near North Base at Edwards Air Force Base.

The cause of the crash was immediately understood and attributed to the failure of the single total pressure source. The test team began a review of all other single point failures that could potentially cause the loss of an airplane. This review clearly indicated that the hazard analysis required updating. The updated hazard analysis found that airplane modifications were required to operate safely in the current environment and in the proposed low altitude air show environment. The test team identified improvements that were required in the redundancy management of pitot-static pressures, INU data, and measurements in airspeed and sideslip. In addition to fixes required as a direct result of the mishap and hazard review, other airplane improvements were identified to support the low altitude flight demonstration. These modifications and improvements are summarized in table I.

Table I

X-31 Significant Modifications and Improvements

Modification/Improvement	Hardware or Software	Reason
Heated Rosemont Kiel Probe	H/W	Return to Flight[1]
Replumb Standby Airspeed Indicator and Secondary Airdata Source		
VHF Antenna and VHF Radio Activation		Paris/Low Altitude Post-Stall (PST)
Redundant A8 Sensor		
Drag Chute System Installation		
Flight Control Law Changes for Low Altitude (V122)	S/W	
INU Utilization for Manching/Paris		
Beta Vane Monitor		Return to Flight
Airdata Monitor		
HUD Above Ground Level/Mean Sea Level (AGL/MSL) Switch		Paris/Low Altitude PST
PLA and PT56 on DDI		
INU Monitors		Return to Flight
A8 Monitor		Paris/Low Altitude PST
Noseboom AOA Threshold		Return to Flight
INHIBIT FCS Reset in Request Mode		
Reversionary (R)-mode Changes		Paris/Low Altitude PST
PST Entry Speed limited to 240 KEAS		
Mach Number Observer		Return to Flight
Gain Set for Low Altitude PST		Paris/Low Altitude PST

Note: (1) Return to flight following A/C #1's mishap.

With these modifications in place, the X-31 returned to flight on 13 April 1995. The redundancy management improvements made the X-31 a safer airplane and better suited for the low altitude post-stall maneuver demonstration. The mishap highlighted the need to review flight hazards in detail and on a periodic basis as the scope and requirements of a program change.

LOW ALTITUDE POST-STALL MANEUVERS

Performing low altitude (500 ft above ground level (AGL)) post-stall maneuvers presented unique safety challenges. Previously, the X-31 had only flown post-stall maneuvers above 10,000 ft, where a safe recovery from post-stall was possible, even in the event of a departure and spin chute deployment. The flight envelope would be expanded down to 500 ft where the spin chute would be of little value and a departure would likely result in the loss of the airplane. It was also required that the airplane be safely recoverable with a first failure of the flight control system. The X-31 flight control redundancy management system was designed for post-stall maneuvers above 10,000 ft, and certain failures would not allow a recovery from some post-stall maneuvers at low altitude. The X-31 team resolved the above issues by using the same engineering and safety processes it had been using throughout the flight test program.

Simulation was used to define a candidate maneuver set for the air show. A candidate maneuver was required to be within the previously cleared AOA and airspeed post-stall envelope (70 deg AOA, 265 KEAS maximum PST entry airspeed, and 70 KEAS minimum airspeed), be repeatable, provide safe ground clearance, have a safe recovery after a failure, and conform to the airspace and maneuver restrictions at Paris. The simulation identified some basic rules for a post-stall maneuver near the ground:

1. Recovery from a high rate of descent post-stall maneuver was required by 3,000 ft AGL.

2. For low altitude post-stall maneuvers below 1,000 ft AGL, the velocity vector had to remain level or above the horizon.

3. For post-stall rolls below 1,000 ft AGL, the roll was required to be in a wings up direction.

4. Extended post-stall maneuvers below 1,000 ft AGL had to be at 50 deg AOA or below.

Throughout the development of the air show routine, the simulator was used to screen candidate maneuvers, practice recoveries from failures, and link maneuvers for the final demonstration sequence. The Flight-Hardware-In-The-Loop Simulation at NASA Dryden was used for failure simulations and the Rockwell dome simulator was used for integrated air show development. It would have been impossible to develop the air show in the time and sorties allowed without high fidelity manned simulators.

Initial flight tests began at 13,000 ft (Mean Sea Level (MSL)) to verify the new flight control software load at flight conditions previously flown. The air show maneuvers were also flown individually starting at 13,000 ft MSL. All normal flight test procedures were used including telemetry, control room, spin chute, and chase. Emphasis was placed on the air show maneuvers, but clinical tests (step inputs, bank to bank rolls, etc.) were also used to confirm normal airplane flying qualities. The next test altitude was 5,000 ft AGL. At this altitude, the spin chute was not armed since an inadvertent deployment was viewed as more of a risk than the benefits provided. Each maneuver was flown by each pilot before going below 5,000 ft AGL. The pilots were the final authority on when they were ready for a lower altitude. At 2,000 ft AGL, all maneuvers were flown over a marked runway (lakebed or Edwards main base). Chase was not used since it was not possible or safe to remain in a close position, a landing runway was nearby, and the control room was operating. The next altitude was the air show altitude of 1,000 ft to 500 ft AGL. Once the pilots were comfortable with each maneuver at 500 ft, practice of the complete air show sequence began at 2,000 ft AGL and proceeded to 500 ft. The final air show practices were performed as close to the actual Paris air show conditions as possible. This included air show fuel loads, precise takeoff times, precise landing times, and simulated 8,700 foot runway with a drag chute landing. From 13 April to 16 May 1995, 36 flights were flown with three pilots in preparation for the air show. The

maneuvers selected for the air show were safe and well within the capabilities of the airplane and pilots. Focused, intensive air show practice and disciplined flight test procedures were required to safely prepare an airplane and pilots for a flight demonstration.

CUTTING THE TELEMETRY CORD

Taking a research vehicle away from its home base and its real time telemetry required special safety considerations not required of an operational airplane. Airplane modifications and special procedures were required to reduce the risks.

The test team determined that by modifying hardware, software, and procedures, the X-31 could safely fly in Paris without telemetry (TM). To insure a robust control system and safe, predictable airplane flying qualities, the air show routine was flown many times, including in conditions of high winds or gusts. Any maneuver not providing a wide control margin was eliminated from the air show, since TM would not be available to provide safety calls for marginal maneuvers. By the conclusion of the air show development, the team was confident in the outstanding, safe flying qualities of the airplane. During all previous flight test operations, the control room was relied upon to provide critical information to the pilot in the event of a problem. To reduce this dependency on the control room, additional automatic redundancy management routines and new displays formats were included in the new flight control software. In addition to the new software, all flights without a control room used a "mini-monitor room". This consisted of a van with a radio and a small control room team, which included an X-31 pilot, flight control expert, engine expert, and systems engineer. During final rehearsal flights at Dryden, the "mini-monitor room" was used to support the flights with the Dryden control room monitoring but silent. This arrangement was used for all flights in Europe and was a key factor in the safe operations of an "X-Airplane" away from its home base.

WEATHER

Weather is a challenge for all air show performers but it offered additional concerns for the X-31. As normal with many research airplanes, the X-31 was prohibited from flying in clouds or instrument meteorological conditions. It was required to remain a dry airplane since many of the airplane compartments were not watertight and the thrust vector vanes were sensitive to moisture.

The weather restrictions were most critical to X-31 during the ferry flights between Manching, Germany and Paris, France. The airplane had to remain clear of clouds and moisture for the entire route. A direct flight between Paris and Manching was at the limit of the X-31's range and allowed little margin for route deviations due to weather. It was decided to two-leg it to Paris with an enroute stop at Köln-Bonn, Germany. Though the stop meant good weather was needed at three locations, it provided for large fuel reserves, which allowed route and altitude changes to remain clear of clouds and rain. To get the best possible weather forecast, we conducted face-to-face weather briefs with the weather forecaster with our German Air Force chase pilots providing translation. As an additional safety feature, a hand-held GPS was mounted in the X-31 to provide navigation if separated from the chase aircraft in poor weather conditions. These procedures allowed the X-31 to be safely ferried during a period when weather conditions at Paris changed rapidly from acceptable to unacceptable.

For the air show, weather minimums were strictly observed:

1. 5,000 foot ceiling for the full demonstration;
2. 1,500 foot ceiling for the poor weather demonstration;
3. Crosswind limit of 10 KTS with gusts to 15 KTS;
4. Tailwind limit of 10 KTS;
5. No rain; and
6. 5 km visibility.

These limits were established during air show preparation at Dryden and were real limits. They were not changed once at Paris.

STOPPING A FAST AIRPLANE ON A RELATIVELY SHORT RUNWAY

The X-31 had only operated from runways greater than 12,000 ft long and its 170 KCAS landing speed presented a challenge for operations on shorter runways. The safety issues involved the usual concerns with potential brake fires, anti-skid failures, blown tires, energy absorption, and departing the runway if unable to stop. A drag chute system was designed to provide for safe takeoffs and landings on shorter runways (<10,000 ft) in Europe and to reduce the wear and tear on the brake system. It was a complex design and replaced the original spin chute system, which had been utilized throughout the X-31 program. Development took longer than expected and initial tests resulted in several problems, which delayed the development to the point that only six deployments had been accomplished prior to the transfer to Europe. The test team developed an alternative brakes-only landing option. Initial landing studies predicted brakes-only landings in Europe would routinely place brake energies in the caution area. Emergency heavy weight landings or aborted takeoffs would place brake energy in the danger area with the risk of brake failure. The test team performed an exhaustive takeoff and landing test program to ensure safe operations in Europe.

Drag chute testing was conducted at Dryden to verify deployment/jettison functions, maximum deployment speed, minimum jettison speed, and crosswind limits. The drag chute provided for safe takeoff aborts and landings on runways as short as 6,000 ft. Maximum performance braking tests were conducted to verify performance of the anti-skid system, brake energy capabilities, brake system usage, and to produce accurate braking performance charts. The results of the braking tests indicated that a reduction in landing speed of 8 KCAS was required for safe no-chute landings on a 10,000 ft runway. The normal 12 deg AOA landing was increased to 13 deg AOA and tested satisfactorily. At the conclusion of the takeoff/landing tests, it was demonstrated that the X-31 could routinely operate on short runways (<8,000 ft) with the drag chute, and could safely land on a

10,000 ft runway in the event of a drag chute failure. Though two drag chute material failures occurred, alternate landing procedures prevented any incidents from occurring. Well thought out normal and emergency takeoff and landing procedures insured the safe operation of a fast airplane on relatively short runways.

DEVELOPMENT OF AIR SHOW EMERGENCY PROCEDURES

Taking a research airplane designed for air combat tests above 10,000 ft to the Paris Air Show required a close review and modification of the emergency procedures. Specific changes in procedures were required for no control room operations, incorporation of the drag chute, the new V122 flight control law software, low altitude operations, and flight operations in Europe.

Since an immediate landing was possible during the air show, emergency procedures were modified to include only the procedures required for a safe landing. The abbreviated procedures fit on a standard knee board card and could be rapidly reviewed by the pilot. The ground team was also prepared to assist the pilot with the abbreviated procedures if required.

Low altitude immediate action procedures were developed for critical failures. These procedures had to be simple, few in number, and minimize the need for complex decision making by the pilot. The immediate action low altitude procedures used for the X-31 are listed below:

1. FCS WARNING-LOW ALTITUDE
    1. Establish positive rate of climb
    2. Set AOA < 15 deg, airspeed > 200 KIAS

2. LOSS OF THRUST-LOW ALTITUDE
    1. Select military
    2. Establish 230 KIAS climb
       If climb not possible:
    3. Eject

3. OUT OF CONTROL-LOW ALTITUDE

$\geq$ 2000' AGL

1. Controls - neutral
2. If ground clearance not assured by 1000' AGL - Eject

$\leq$ 2000, AGL

1. Eject

These procedures were developed by the pilots and chief engineers and then briefed to the program managers of the ITO. Fortunately, no serious problems occurred. It was imperative that low altitude emergency procedures be developed for the air show environment.

THE AIR SHOW ROUTINE

The final air show routine consisted of four basic X-31 signature maneuvers as shown in figures 3-6. The team also designed a "low show" in case of low ceilings which consisted of performing two Mongoose and one Herbst Turn maneuvers. An important safety aspect of these routines was that each maneuver was a separate entity. Most air show routines consist of maneuvers that flow into one another and thus are dependent on each successive maneuver. Since each X-31 maneuver was a separate event, the emphasis on maneuver safety and quality could be more tightly focused. These separate events were easily simulated and the failure matrix was well defined. In addition, due to the two-week "down" period required to disassemble the airplane and transport it to Europe, the pilots had limited practice before arriving in Paris. This relative lack of practice had less of an impact because the air show routine was a series of discrete separate demonstration maneuvers. The timing and precision necessary during a sequenced flowing routine would have required much more practice. Since the main purpose for going to Paris was to showcase the X-31 thrust vectoring technology, separate discrete maneuvers were the safest and most effective method for the demonstration.

FLIGHT CLEARANCE PROCESS

The safety of flight responsibility for the X-31 airplane at the Paris Air Show rested with the U.S. Navy. The Navy had relinquished this authority to NASA in early 1992 when the X-31 airplanes were transferred to NASA. Safety of flight transfer back to the Navy presented several challenges. First, no one in the flight clearance authority, the Naval Air Systems Command (NAVAIR) in Washington, D.C., had participated in the program for more than 3 years. A large volume of testing and significant hardware and software modifications had been made to the airplanes during that period. Second, the schedule to complete the flight safety transfer was extremely tight. The Paris Air Show would begin on 10 June 1995 with or without the X-31. Third, the program was recovering from A/C #1's mishap with the resultant hardware and software modifications to the airplane in development. To successfully transfer the safety of flight to the Navy on a schedule that would support preparation for Paris and the Air Show, several strategies were developed and used:

1. Focus the scope of the data transfer to changes to the airplane as a result of the mishap and special issues for operations in Europe;

2. Use NAVAIR clearance authority personnel that were previously on the X-31 program as much as possible;

3. NASA would retain safety of flight until the low altitude envelope expansion was complete;

4. A team approach was used with direct and frequent transfer of data (telecons daily with NAVAIR, videocon, faxes, etc.);

5. Provide the flight clearances in two phases. An initial clearance for air show practices at Edwards then a final clearance for European operations; and

6. Have a Navy flight test engineer at NASA Dryden to facilitate the clearance process.

It was the responsibility of the X-31 team to do its homework, and demonstrate to the NAVAIR flight clearance

authority that the airplane was safe to operate within the intended envelope for the specified number of flights. The NAVAIR flight clearance process specifically covered flight controls, flying qualities, structures, propulsion, subsystems, and systems safety. The NAVAIR clearance process also provided a critical independent safety review of the X-31 systems and procedures. The first Navy clearance was received on 3 May and air show practice began the following day. After resolving potential electromagnetic interference concerns to the flight control system when in Europe, the second clearance was approved on 25 May and flight operations began in Germany on 29 May.

PARIS AIR SHOW RESULTS

During the four practice sessions and eight air shows at Paris, the X-31 was the "star" of the air show and dramatically demonstrated integrated multi-axis thrust vectoring. The flight demonstration showed that multi-axis thrust vectoring provides a new design dimension, has matured, and is ready for operational development. Post-stall maneuvers had never been demonstrated at these altitudes and included the following firsts:

1. 70 deg AOA down to 500 ft AGL;

2. Fully controlled and stabilized flight at 70 KIAS, above 50 deg AOA at 500 ft AGL; and

3. High rate velocity vector rolls at 70 deg AOA.

The X-31 was a survivor of the Paris Air Show because the same flight test discipline and safety standards that had been used throughout the X-31 program were applied to air show preparation and the Paris Air Show itself.

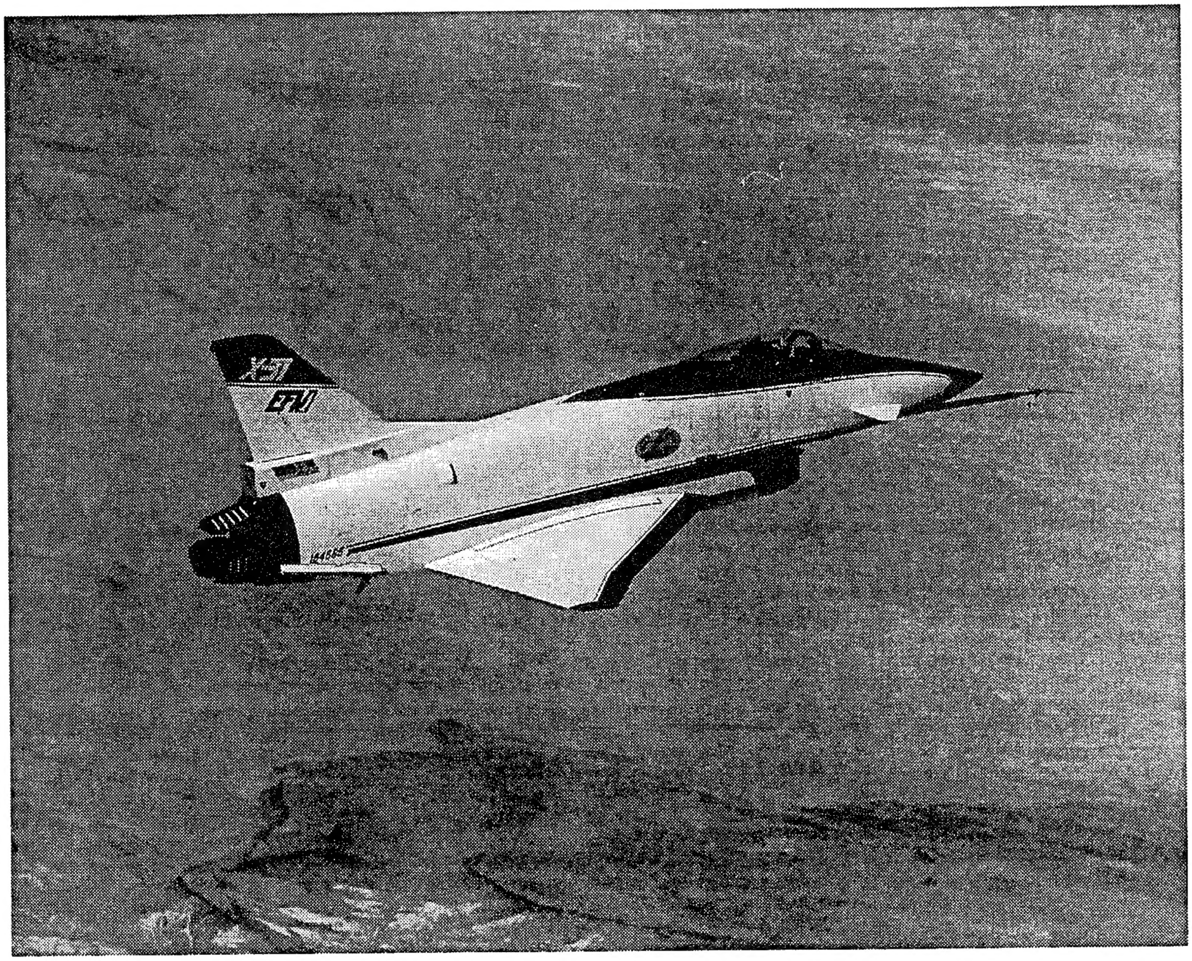


Figure 1. X-31A Airplane

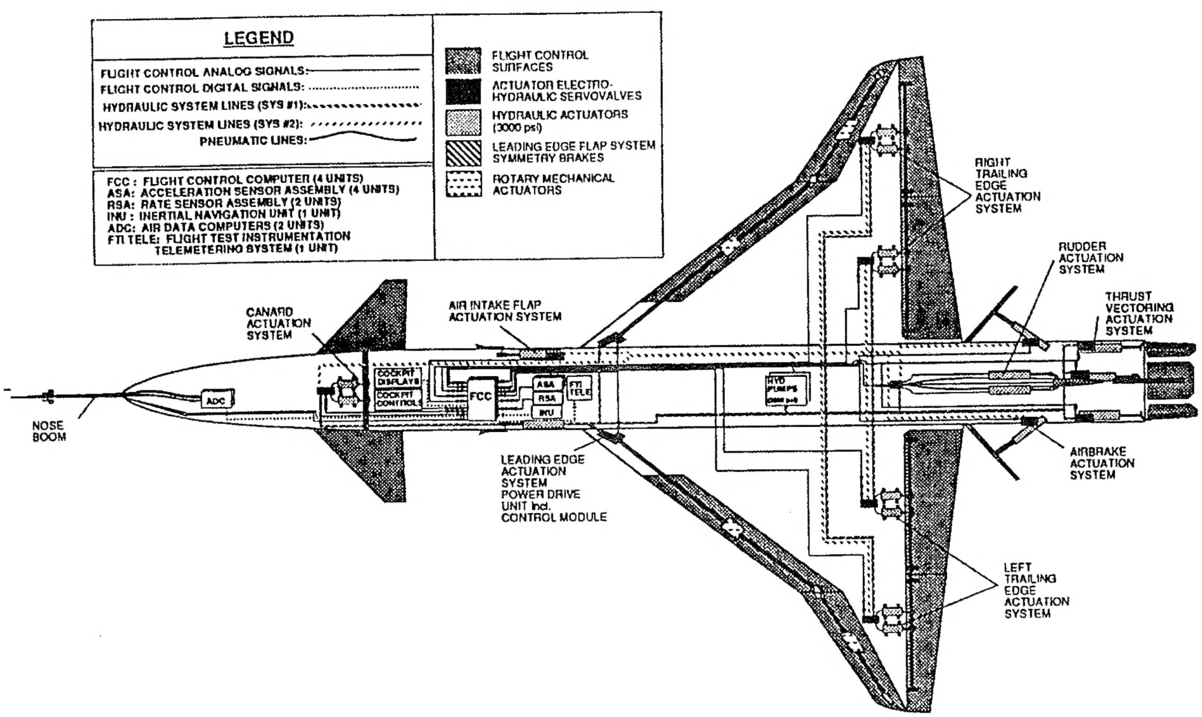
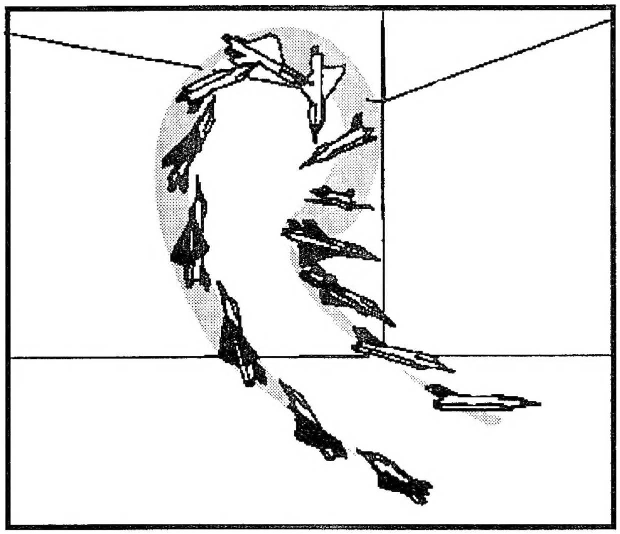


Figure 2. X-31A Flight Control System

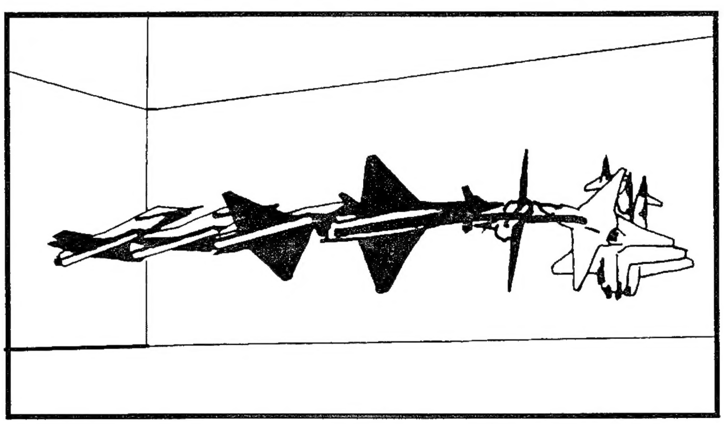
Figure 3. First "Helicopter" Loop



PST Loop with 150° Heading Reversal

Pull 2.0 g then maintain 20° AOA*
When VV* passes horizon (inverted)
Pull to 70° AOA
At 70° AOA 150° left PST roll (Velocity Vector Roll)
Command below 30° AOA

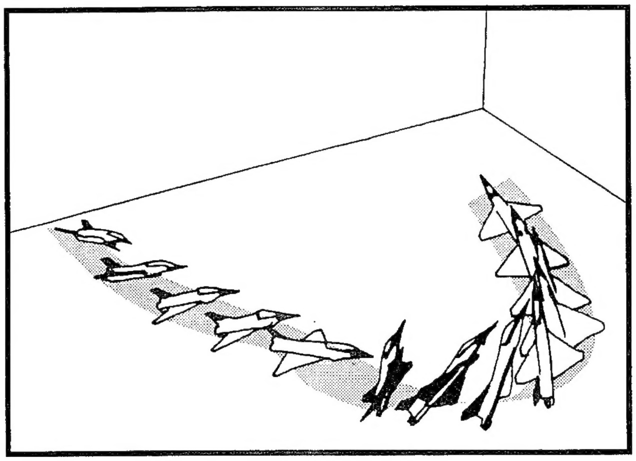
Figure 4. Mongoose



Mongoose

At 180 - 200 KIAS* roll to 70° - 90° left bank
Pull to 70° AOA
Continue to opposite heading
Maintaining 70° - 90° left bank slice nose
up right (Velocity Vector Roll) to vertical nose position
Reduce to 50° AOA
Fly out straight and accelerate

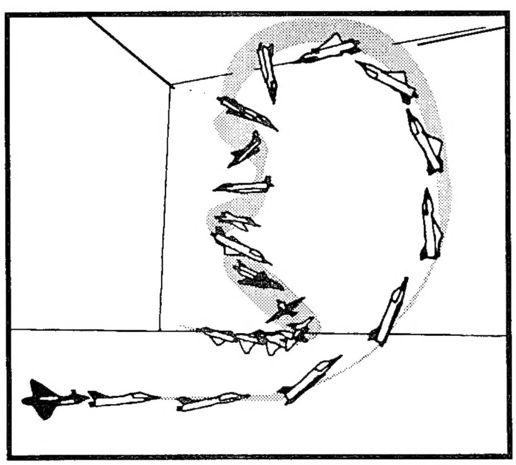
Figure 5. Herbst Turn



Herbst Turn

Stabilize in 30° AOA level flight
Pull to 70° AOA
Reduce to 50° AOA
Stabilize into a 50° AOA left climbing turn
execute a 150° heading change
Return to level flight and accelerate

Figure 6. Second "Helicopter" Loop



PST Loop with 180° / 90° (180°) Heading Reversal

Pull 3.0 g then maintain 15° - 17° AOA
When VV passes horizon (inverted)
Pull to 70° AOA
At 70° AOA 180° left PST roll, stop and
reverse to 90° (180°)
Command AOA below 30°